

# PAIR LOADING IN GAMMA-RAY BURST FIREBALL AND PROMPT EMISSION FROM PAIR-RICH REVERSE SHOCK

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*Draft version February 2, 2008*

## ABSTRACT

Gamma-ray bursts (GRBs) are believed to originate from ultra-relativistic winds/fireballs to avoid the “compactness problem”. However, the most energetic photons in GRBs may still suffer from  $\gamma - \gamma$  absorption leading to  $e^\pm$  pair production in the winds/fireballs. We show here that in a wide range of model parameters, the resulting pairs may dominate those electrons associated with baryons. Later on, the pairs would be carried into a reverse shock so that a shocked pair-rich fireball may produce a strong flash at lower frequencies, i.e. in the IR band, in contrast with optical/UV emission from a pair-poor fireball. The IR emission would show a 5/2 spectral index due to strong self-absorption. Rapid responses to GRB triggers in the IR band would detect such strong flashes. The future detections of many IR flashes will infer that the rarity of prompt optical/UV emissions is in fact due to dust obscuration in the star formation regions.

*Subject headings:* gamma-rays: bursts — radiation mechanisms: nonthermal — relativity

## 1. INTRODUCTION

There is little doubt that GRBs arise from relativistically expanding winds/fireballs, which also drive relativistic blast waves that responsible for later time emission at X-ray, optical and radio bands (see reviews of Piran 1999; van Paradijs, Kouveliotou & Wijers, 2000; Cheng & Lu 2001; and Mészáros 2002). The observed GRB spectra are hard, with a significant fraction of the energy above the  $e^\pm$  pair formation energy threshold, so it is believable that there are processes of substantial pair production related to GRBs. One case of  $e^\pm$  pair production in GRBs is that the GRB photons are back-scattered by the ambient medium and interact with other outgoing high-energy GRB photons, leading to  $e^\pm$  pair production and then deposition of momentum into the external medium. Such a case has been considered by Madau & Thompson (2000); Thompson & Madau (2000); Dermer & Böttcher (2000); Madau, Blandford & Rees (2000); Mészáros, Ramirez-Ruiz & Rees (2001); Beloborodov (2002); Ramirez-Ruiz, MacFadyen & Lazzati (2002), which could be called an “external case”. In this paper, we consider the so-called “internal case”, in which pairs are produced within the relativistic fireball due to  $\gamma - \gamma$  absorption between high energy photons, and the formed pairs remain mixing in the fireball matter. The pairs in the external medium (external case) will modify the usual properties of the forward shock and then the later afterglow, while the pairs in the wind/fireball (internal case) affect the reverse shock that is responsible for prompt emission in soft bands during the bursting phase. Pilla & Loeb (1998) have also studied spectral signatures of GRBs by considering pair production in fireballs. It is possible that the pairs are so abundantly generated that the fireball becomes optically thick, and the GRB photons undergo Compton multi-scattering before leaking out. Mészáros et al. (2002) discussed this case to account for the currently known X-ray flashes.

A large Lorentz factor is required to avoid the “compactness problem” in GRBs (see, e.g., Piran 1999). However, the high-energy photons may still suffer from absorption, and the generated pairs may dominate the electrons associated with baryons, and then change the conditions in the reverse shock. The pres-

ence of a large number of  $e^\pm$  pairs decreases the shared energy per lepton in the reverse shock, so that the reverse flash is softened to lower frequencies. The reverse-shock model (Sari & Piran 1999; Mészáros & Rees 1999) has been successful to interpret the strong optical flash detected in GRB 990123 (Akerlof et al. 1999). Here we show that a pair-rich reverse shock gives rise to even stronger radiation in longer wavelength, e.g. the IR, as opposed to the UV/optical. We discuss in §2 the pair production, and in §3 the effect of pairs on the prompt flashes from reverse shocks. We discuss the current observation of prompt optical radiation in §4. Conclusions and discussion on future observations are given in §5.

## 2. PAIR LOADING IN GRBS

### 2.1. GRB emission site

Consider a GRB central engine producing a relativistic wind outflow, which carries energy from the center to some radius that GRB emission arises. We assume the isotropic geometry, which is valid even for a jetted GRB as long as the Lorentz factor  $\Gamma > 1/\theta_{jet}$ , with  $\theta_{jet}$  the jet opening angle. The width of outflow is  $\Delta \lesssim 10^{12}$  cm for a wind lasting a duration of  $\lesssim 100$  s. The emission energy may come from two energy forms, the kinetic energy of the baryon bulk and the magnetic energy of the fireball. Therefore the initial wind/fireball energy  $E$  may be divided into two components (e.g. Zhang & Mészáros 2002). The first component is the bulk kinetic energy  $E_K$  that, as considered in the simplest fireball model, comes from the thermal energy of photons, pairs and baryons after initial acceleration. The second component is the energy  $E_P$  of the Poynting flux from the central engine. Define  $\sigma \equiv E_P/E_K$ , then the fireball is Poynting-flux dominated if  $\sigma \gtrsim 1$ , as suggested by recent detection of extreme polarization in GRB 021206 (Coburn & Boggs 2003), or kinetic-energy dominated if  $\sigma \lesssim 1$ .

The non-thermal spectra of GRBs require that the site of GRB emission should be beyond the photospheric radius at which the outflow becomes optically thin to scattering by electrons associated with baryons. The total baryonic electron number in the fireball is  $N_b = E/(1 + \sigma)\Gamma m_p c^2$ , with  $\Gamma$  the

Lorentz factor of the fireball. Thus the related optical depth  $\tau_b = \sigma_T N_e / 4\pi R^2 \lesssim 1$  leads to a lower limit to the emission radius,

$$R_b = 3.4 \times 10^{13} E_{52}^{1/2} \Gamma_{300}^{-1/2} (1 + \sigma)^{-1/2} \text{cm}. \quad (1)$$

Hereinafter, we use c.g.s. units and the convention  $U_x = U/10^x$ , except for the Lorentz factors which are scaled as  $\gamma_x = \gamma/x$ . Since  $R_b \propto \tau_b^{-1/2}$  is insensitive to  $\tau_b$ ,  $R_b$  in the above equation do not change much even though the GRB photons undergo a few times scattering,  $\tau_b \sim$  a few (not possible to be quite large). It is seen that usually  $R_b \gg \Delta$ , so the emission region of GRBs can be regarded as thin shells.

GRB light curves at gamma-ray energy are often highly variable with time scale  $\delta t \sim 1 \text{ ms} - 1 \text{ s}$ . Because of radiation beaming an observer can see only the part of the emitting fireball sphere up to an angle  $\Gamma^{-1}$  from the line of sight. The sphere curvature leads to a delay in the photon arrival time by  $R/2\Gamma^2 c$ . This so-called angular spreading time should not be larger than the observed variability time scale  $\delta t$ , which yields an upper limit to  $R$

$$R_{var} = 5.4 \times 10^{14} \Gamma_{300}^2 \delta t_{-1} \text{cm}. \quad (2)$$

Thus, from the properties of GRB spectra and light curves we can constrain the emission site to the regime

$$R_b \lesssim R \leq R_{var}. \quad (3)$$

We may take the typical radius as  $R = 10^{14} R_{14} \text{cm}$  in the following.

### 2.2. Pair loading

For an initially thermal-energy-dominated GRB fireball, pair production in GRBs begins in the fireball acceleration phase when the fireball is still opaque to photons, but the pair number density decreases exponentially with increasing radius during this phase (Shemi & Piran 1990). When the fireball becomes transparent to Compton scattering, the pair number has been negligible compared with baryonic electrons. We neglect the pair production in this case.

The intense pair production may occur in the bursting phase due to  $\gamma$ - $\gamma$  absorption between GRB photons. For the most energetic photons at the high-energy end of the spectrum, the optical depth of  $\gamma$ - $\gamma$  absorption may exceed unity. Thus, they will not escape freely from the fireball, and will produce  $e^\pm$  pairs. The pairs will remain in the fireball, with the same bulk Lorentz factor as the fireball (static in the comoving frame). We here calculate how many  $e^\pm$  pairs generated in this process.

The observed photon spectra of GRBs can be approximated by a broken power-law, with a high-energy portion of the form  $N_\epsilon \propto \epsilon^{-\beta}$  for  $\epsilon > \epsilon_b$ , where  $\epsilon = h\nu/m_e c^2$  is the photon energy in units of the electron's rest energy, and  $\epsilon_b \sim 1$  is the break energy above which the index  $\beta \sim 2 - 3$ . The photon number above a certain energy  $\epsilon$  is, therefore, approximated as

$$N_{>\epsilon} = \left( \frac{\beta - 2}{\beta - 1} \right) \frac{E_\gamma}{\epsilon_b m_e c^2} \left( \frac{\epsilon}{\epsilon_b} \right)^{-(\beta-1)}, \quad (4)$$

where  $E_\gamma$  is the GRB energy emitted in gamma-rays.

A photon with energy  $\epsilon$  may annihilate any photons above  $\epsilon_{an} = \Gamma^2/\epsilon$ . Its optical depth due to  $\gamma$ - $\gamma$  absorption is approximated in an analytical approach by Lithwick & Sari (2001) as

$$\tau_{\gamma\gamma}(\epsilon) = \frac{(11/180)\sigma_T N_{>\epsilon_{an}}}{4\pi R^2}. \quad (5)$$

A photon  $\epsilon$  with  $\tau_{\gamma\gamma}(\epsilon) > 1$  would be absorbed in the fireball. Setting  $\tau_{\gamma\gamma}(\epsilon_{cut}) = 1$  results in a cut-off energy

$$\epsilon_{cut} = 400 E_{\gamma,52}^{-\frac{1}{\beta-1}} \epsilon_b^{-\frac{\beta-2}{\beta-1}} \Gamma_{300}^2 R_{14}^{\frac{2}{\beta-1}}, \quad (6)$$

where the numerical coefficient on the right-hand side corresponds to typical parameter  $\beta = 2.2$  (Preece et al. 2000). The observed GRB spectrum above cut-off energy  $\epsilon_{cut}$  should be attenuated. *EGRET* on board the *Compton-GRO* satellite have detected several GRBs emitting very high energy gamma-ray tails. If the cut-off energy can be detected by future satellites such as *GLAST*, we can constrain the emission radius and the initial Lorentz factor, which are the most important physical parameters in GRBs. For examples, if no significant attenuation above 1 GeV,  $\epsilon_{cut} m_e c^2 > 1 \text{ GeV}$ , this yields a limit

$$R > R_{cut}(1 \text{ GeV}) = 2.6 \times 10^{14} E_{\gamma,52}^{1/2} \epsilon_b^{(\beta-2)/2} \Gamma_{300}^{-(\beta-1)} \text{cm}. \quad (7)$$

The photons above  $\epsilon_{cut}$  would be absorbed for  $e^\pm$  production, and each absorbed photon corresponds to a pair of  $e^\pm$ . Integrating the photon spectrum above  $\epsilon_{cut}$  we have the total number of the resulting pairs

$$N_\pm = 1.5 \times 10^{54} E_{\gamma,52}^2 \epsilon_b^{2(\beta-2)} \Gamma_{300}^{-2(\beta-1)} R_{14}^{-2}, \quad (8)$$

and hence the ratio

$$k_\pm \equiv N_\pm / N_b = 69 E_{\gamma,52}^2 \epsilon_b^{2(\beta-2)} \Gamma_{300}^{-(2\beta-3)} E_{52}^{-1} (1 + \sigma) R_{14}^{-2}, \quad (9)$$

where we have scaled both  $E$  and  $E_\gamma$  in units of  $10^{52}$  ergs assuming that the efficiency of a GRB is significant. We note that the calculation of  $e^\pm$  number in Eq. (8) does not depend on detailed models of energy dissipation in emission region, e.g. internal shock model or magnetic dissipation model. Our calculation is based on observations of GRB properties, i.e. spectral and temporal profiles.

Eq. (9) infers that  $k_\pm$  is sensitive to  $R$ . The condition for strong pair loading, i.e.  $2k_\pm > 1$ , is

$$R < R_{load} = 1.2 \times 10^{15} E_{\gamma,52} \epsilon_b^{\beta-2} \Gamma_{300}^{-(\beta-\frac{3}{2})} E_{52}^{-1/2} (1 + \sigma)^{1/2} \text{cm}. \quad (10)$$

The case  $2k_\pm > m_p/m_e$  in which pair mass dominates baryon mass is even achieved if  $R < R_{dom} = R_{load} (m_p/m_e)^{-1/2}$ . From Eqs. (9) and (10) we can see that a wind/fireball with typical parameters generally becomes pair rich in the bursting phase. These secondary pairs are possible to form an optically thick screen again for the GRB emissions (e.g. Guetta, Spada & Waxman 2001; Kobayashi, Ryde & MacFadyen 2002; Mészáros et al. 2002). The optical depth due to Compton scattering by pairs is  $\tau_\pm = \sigma_T (2N_\pm) / 4\pi R^2$ . Substituting Eq. (8) into  $\tau_\pm = 1$  leads to

$$R_\pm = 2.4 \times 10^{14} E_{\gamma,52}^{1/2} \epsilon_b^{(\beta-2)/2} \Gamma_{300}^{-(\beta-1)/2} \text{cm}. \quad (11)$$

A classic GRB takes place in the site optically thin to scattering, so the emission radius should be large with  $R \gtrsim R_\pm$ . Also the permitted regime of Eq. (3) for optically thin GRBs is changed

to  $R_{\pm} \lesssim R \leq R_{var}$ . If  $R \lesssim R_{\pm}$ , the wind/fireball is optically thick. However the generated pairs cannot build up an optical depth substantially exceeding unity, and Compton multi-scattering degrades the photons into X-ray energy. This gives an interpretation of X-ray flashes (Mészáros et al. 2002)<sup>1</sup>.

Fig. 1 shows the above special radii in the  $\Gamma - R$  diagrams, where the GRB parameter space is separated into different regions.

### 3. PROMPT FLASHES FROM PAIR-RICH REVERSE SHOCKS

After the bursting phase, the fireball cools into a cold shell, which continues to expand at an ultrarelativistic speed and with kinetic energy  $E_a$ . This afterglow energy should be less than the initial wind/fireball energy after the burst, and  $E_a \lesssim E - E_{\gamma}$ . When the cold shell runs into the surrounding medium, the kinetic energy is dissipated into internal energy, which gives rise to prompt emission and long-term afterglow. Sari & Piran (1999a, 1999b) and Mészáros & Rees (1999) (see also Mészáros, Rees & Papathanassiou 1994; Mészáros & Rees 1997; Panaitescu & Mészáros 1998) have discussed the prompt emission in the context of GRB 990123, assuming no-pair fireball. We discuss here the prompt emission from a pair-rich fireball.

The interaction between the shell and the surrounding medium forms two shocks: a reverse shock that propagates into the cold shell, increasing its internal energy then giving rise to a prompt flash; and a forward shock that propagates into the cold medium and produces a long-term multiwavelength afterglow. The shocked medium and shell material are in pressure balance and separated by a contact discontinuity. There are four regions of distinct properties: the unshocked surrounding medium (denoted “1”), the shocked medium (“2”), the shocked shell material (“3”) and the unshocked shell (“4”).

Now the reverse shock may propagate into a pair-rich shell, with lepton number density  $n_{e,4} = (1 + 2k_{\pm})n_{b,4}$  and mass density  $\rho_4 = n_{b,4}m_p[1 + 2k_{\pm}(m_e/m_p)]$  (both in rest frame of region 4). The shocked material in region 2 and 3 moves together, thus they have the same Lorentz factor,  $\gamma_2 = \gamma_3$ . The Lorentz factor of the reverse shock relative to region 4 is  $\gamma_{3,4} \simeq \gamma_4/\gamma_3$ . The shock jump conditions yield that the internal energy and lepton number density of the shocked shell material are  $U_3 \simeq 4\gamma_{3,4}^2\rho_4c^2$  and  $n_{e,3} = 4\gamma_{3,4}n_{e,4}$ , respectively (Blandford & McKee 1976). Let a fraction  $\xi_e$  of the internal energy goes into leptons, including the baryonic electrons and secondary pairs. These shocked leptons are expected to be in a power-law distribution:  $dn_{e,3}/d\gamma_e \propto \gamma_e^{-p}$  for  $\gamma_e > \gamma_m$ , with  $p \approx 2$ .

The emission reaches a peak when the reverse shock crosses the inner edge of the shell at

$$t_{cr} = \max[\Delta/c, t_{dec}] \quad (12)$$

(Sari & Piran 1999b) with the deceleration time

$$t_{dec} = 3.4E_{a,52}^{1/3}n_1^{-1/3}\gamma_{4,300}^{-8/3} \text{ s}. \quad (13)$$

The Lorentz factor of shocked shell at  $t_{cr}$  could be estimated as

$$\gamma_3 = \left( \frac{3E_a}{32\pi n_1 m_p c^5 t_{cr}^3} \right)^{1/8} = 230 \left( \frac{E_{a,52}}{n_1} \right)^{1/8} t_{cr,1}^{-3/8}. \quad (14)$$

<sup>1</sup>Strictly speaking, the way we calculate the pair number is only valid for optically thin bursts. However,  $\tau_{\pm}$  is not large, and the spectral break energy is degraded no more than an order of magnitude. Furthermore, the calculation of pair numbers is insensitive to the break energy provided  $\beta \sim 2$ . Therefore, our calculation for optically thick case here is still valid.

We will focus now on the emission at the peak time  $t_{cr}$ .

The characteristic Lorentz factor (in the rest frame of region 3) of the accelerated leptons is therefore

$$\gamma_m = \xi_e \frac{U_3}{n_{e,3}m_e c^2} = \xi_e \mu (\gamma_4/\gamma_3), \quad (15)$$

where  $\mu$  is the effective mass per lepton in units of electron mass and is given by

$$\frac{\mu m_e}{m_p} = \frac{1 + 2k_{\pm}(m_e/m_p)}{1 + 2k_{\pm}} \simeq \begin{cases} 1 & \text{for } k_{\pm} \ll 1; \\ (2k_{\pm})^{-1} & \text{for } 1 < 2k_{\pm} < m_p/m_e; \\ m_e/m_p & \text{for } 2k_{\pm} > m_p/m_e. \end{cases} \quad (16)$$

Provided that the characteristic Lorentz factor of leptons is not less than that of baryons, the  $\xi_e$  value is limited to the regime

$$2k_{\pm}m_e/m_p \lesssim \xi_e \lesssim 1 \quad \text{for } 2k_{\pm} < m_p/m_e, \\ \xi_e \approx 1 \quad \text{for } 2k_{\pm} > m_p/m_e. \quad (17)$$

#### 3.1. The $1 < 2k_{\pm} < m_p/m_e$ case

If  $k_{\pm} \gg 1$ , the random Lorentz factor of leptons becomes lower since the lepton number increases significantly. However, the pairs do not change the magnetic field in region 3, which is assumed to have an energy density  $\xi_B$  times of the internal energy density, that is,  $B = \gamma_3 c (32\pi n_1 m_p \xi_B)^{1/2}$  with  $n_1$  being the medium number density. In low- $\sigma$  case, the magnetic field may be shock-induced, thus we assume  $\xi_B \sim 10^{-2}$ , as is apparent in the long-term forward shock-produced afterglow. But in high- $\sigma$  case it may be dominated by the original wind magnetic field, we then expect much higher  $\xi_B$  value. Thus, for  $1 < 2k_{\pm} < m_p/m_e$ , the observed peak frequency of synchrotron photons  $\nu_m \propto \gamma_m^2 B$  is lower by a factor of  $(2k_{\pm})^{-2}$ . Substituting Eqs. (15) and (16) we have

$$\nu_m = \gamma_3 \gamma_m^2 \frac{eB}{2\pi m_e c} = 8.2 \times 10^{10} \xi_e^2 \xi_{B,-1}^{-1} n_1^{1/2} k_{\pm,2}^{-2} \gamma_{4,300}^2 \text{ Hz}, \quad (18)$$

where  $\gamma_3$  is cancelled out in the calculation. Note that the emission is in quite low frequencies, in contrast with the optical/UV for the case without pairs ( $\mu m_e/m_p \approx 1$ ). The cooling frequency is relevant to those leptons cool at the dynamical time  $t$ . For  $t = t_{cr}$  it is

$$\nu_c = 1.1 \times 10^{14} \xi_B^{-3/2} E_{a,52}^{-1/2} n_1^{-1} t_{cr,1}^{-1/2} \text{ Hz}, \quad (19)$$

most sensitive to  $\xi_B$ . If  $\xi_B \sim 10^{-2}$ ,  $\nu_c$  is larger,  $\sim 10^{17}$  Hz.

The pairs also significantly increase the radiative efficiency by increasing the radiating lepton number. At the crossing time  $t_{cr}$ , the reverse shock has swept up all the shell leptons, and the observed emission reaches a peak. The total lepton number is  $N_e \equiv N_b(1 + 2k_{\pm}) \simeq 2N_{\pm}$ , and, with help of Eq. (14), the peak flux is

$$F_{\nu_m} = \gamma_3 N_e \frac{e^3 B}{4\pi d_l^2 m_e c^2} \simeq 960 \frac{\xi_B^{1/2} n_1^{1/4} E_{a,52}^{1/4} k_{\pm,2}}{d_{l,28}^2 \Gamma_{300} (1 + \sigma) t_{cr,1}^{3/4}} \text{ Jy}, \quad (20)$$

where  $d_l$  is the GRB luminosity distance. The flux increases by a factor of  $2k_{\pm}$  as opposed to the case without pair effect.

The synchrotron spectrum of power-law-distributed leptons is simply described by power-law segments: (1) For  $\nu < \nu_m$  we have the synchrotron low-energy tail  $F_{\nu} \propto \nu^{1/3}$ . (2) For  $\nu_m < \nu < \nu_c$  we have the typical synchrotron slope depending on the lepton's distribution,  $F_{\nu} \propto \nu^{-(p-1)/2}$ . (3) For  $\nu > \nu_c$  the spectrum behaves as a fast-cooling slope,  $F_{\nu} \propto \nu^{-p/2}$ . We are particularly interested in the optical prompt emission, say, in the R band at  $\nu_R = 4.5 \times 10^{14}$  Hz, a frequency well above the characteristic frequency  $\nu_m$  and around the cooling frequency  $\nu_c$ . Because of the independence of  $\nu_c$  on  $k_{\pm}$ , no matter whether  $\nu_R$  is above  $\nu_c$  or not we usually have  $F_{\nu_R} \propto F_{\nu_m} \nu_m^{(p-1)/2} \propto k_{\pm}^{-(p-2)}$ . Since  $p \approx 2$ , this means that the emission is insensitive to pair loading. For simplicity  $p = 2$ , we have, for small  $\xi_B$  or  $\nu_R < \nu_c$ ,

$$F_{\nu_R < \nu_c} = 0.41 \frac{\xi_{e,-1} \xi_{B,-2}^{3/4} n_1^{1/2} E_{52} E_{a,52}^{1/4} \gamma_{4,300}}{d_{l,28}^2 \Gamma_{300} (1 + \sigma) t_{cr,1}^{3/4}} \text{ Jy}, \quad (21)$$

and for enough large  $\xi_B$  or  $\nu_R > \nu_c$ ,

$$F_{\nu_R > \nu_c} = 5.8 \frac{\xi_{e,-1} E_{52} \gamma_{4,300}}{d_{l,28}^2 \Gamma_{300} (1 + \sigma) t_{cr,1}} \text{ Jy}, \quad (22)$$

where  $k_{\pm}$  is cancelled out, and  $\Gamma$  and  $\gamma_4$  can be also cancelled out if  $\Gamma \sim \gamma_4$ .

Synchrotron self-absorption may be important at low frequencies here. We follow the simple way by Sari & Piran (1999b) and Chevalier & Li (2000) to estimate the maximal flux emitted by the shocked shell material as a blackbody

$$F_{\nu,bb} \approx \pi \left( \frac{R_{\perp}}{d_l} \right)^2 \frac{2\nu^2}{c^2} kT_{eff}, \quad (23)$$

with the observed size of the fireball  $R_{\perp}$  given roughly by

$$R_{\perp} \approx 2\gamma_3 ct \quad (24)$$

and the effective temperature by

$$kT_{eff} \approx \gamma_3 \gamma_{\nu} m_e c^2 / 3, \quad (25)$$

where  $\gamma_{\nu}$  is the Lorentz factor of the electrons that radiate at the frequency  $\nu$  and is given by  $(2\pi m_e c \nu / \gamma_3 e B)^{1/2}$ . Substituting Eqs. (14), (24) and (25) into Eq. (23) leads to

$$F_{\nu} \leq F_{\nu,bb} \approx 150 \left( \frac{\nu}{\nu_R} \right)^{5/2} \xi_{B,-2}^{-1/4} E_{a,52}^{1/4} n_1^{-1/2} d_{l,28}^{-2} t_{cr,1}^{5/4} \text{ Jy}, \quad (26)$$

where we scale the observed frequency in units of R band frequency  $\nu_R$ . It is obvious that the peak flux in characteristic frequency  $\nu_m$  usually suffers strong self-absorption. If the absorption frequency  $\nu_a$  is defined by  $F_{\nu} = F_{\nu,bb}$ , we should have  $\nu_a > \nu_m$ . Assuming further  $\nu_a < \nu_c$ , we can calculate its value,

$$\nu_a \approx 2.0 \times 10^{14} \left( \frac{\xi_{e,-1} \xi_B n_1 E_{52} \gamma_{4,300}}{\Gamma_{300} (1 + \sigma) t_{cr,1}^2} \right)^{1/3} \text{ Hz}. \quad (27)$$

This is in the IR band,  $\nu_a \sim 4 \times 10^{13}$  Hz, for  $\xi_B \sim 10^{-2}$ . As shown in Fig. 2, the observed spectrum peaks at  $\nu_a$ , and below  $\nu_a$  it behaves as  $F_{\nu} = F_{\nu,bb} \propto \nu^{5/2}$ .

<sup>2</sup>The generated pair number is prevented from multiplying beyond a value corresponding to  $\tau_{\pm}$  of a few, due to self-shielding. If  $\tau_{\pm} < 10$  is required, the regime with  $R < R_{\pm}/\sqrt{10}$  is not relevant to any observed bursts. So the  $2k_{\pm} > m_p/m_e$  case, which requires  $R < R_{dom}$ , do not emerge unless  $R_{dom} > R_{\pm}/\sqrt{10}$  for high  $\sigma$ .

### 3.2. The $2k_{\pm} > m_p/m_e$ case with high $\sigma$

A low- $\sigma$  GRB usually do not produce  $e^{\pm}$  pairs with mass larger than fireball baryons,  $2k_{\pm} > m_p/m_e \sim 1800$ , because that  $R_{dom} < R_b$  (see Fig. 1). However, if  $\sigma \gtrsim 1$  where the initial wind/fireball is dominated by magnetic field, it may appear that  $R_{dom} > R_b$ . So, the  $2k_{\pm} > m_p/m_e$  case may emerge below  $R_{dom}$  and above  $R_b$  in Fig. 1 for high  $\sigma$ . It is usually apparent that  $R_{dom} < R_{\pm}$ , except for  $\sigma \gtrsim 10^2$ , therefore the case  $2k_{\pm} > m_p/m_e$  should be associated with optically thick pair screens, and, as suggested by Mészáros et al. (2002), accompanied with X-ray flashes<sup>2</sup>.

For  $\xi_e \approx 1$  and  $\mu \approx 1$  in this case, from Eq. (15) the characteristic lepton Lorentz factor is simply  $\gamma_m \approx \gamma_4/\gamma_3$ , which is independent of the pair number or  $k_{\pm}$ . The corresponding emitted frequency is

$$\nu_m \simeq 1.1 \times 10^{10} \xi_B^{1/2} n_1^{1/2} \gamma_{4,100}^2 \text{ Hz}, \quad (28)$$

independent of  $\xi_e$  and  $k_{\pm}$ , where we have scaled  $\gamma_{4,100} = \gamma_4/100$  for regime below  $R_{dom}$  in Fig. 1. At the same time, the Eqs. (19), (20) and (26) above are still valid. It should be noticed that the peak time  $t_{cr}$  is larger for lower Lorentz factor,  $t_{cr} \geq t_{dec} = 63 E_{a,52}^{1/3} n_1^{-1/3} \gamma_{4,100}^{-8/3}$  s. We calculate the R-band emission, which is dependent on  $k_{\pm}$ ,  $F_{\nu_R} \propto F_{\nu_m} \nu_m^{(p-1)/2} \propto k_{\pm}$ . It is, for  $\nu_R < \nu_c$ ,

$$F_{\nu_R < \nu_c} = 0.80 \frac{\xi_{B,-2}^{3/4} n_1^{1/2} E_{52} E_{a,52}^{1/4} \gamma_{4,100} k_{\pm 4}}{d_{l,28}^2 \Gamma_{100} \sigma_1 t_{cr,2}^{3/4}} \text{ Jy}, \quad (29)$$

or for  $\nu_R > \nu_c$ ,

$$F_{\nu_R > \nu_c} = 6.9 \frac{E_{52} \gamma_{4,100} k_{\pm 4}}{d_{l,28}^2 \Gamma_{100} \sigma_1 t_{cr,2}} \text{ Jy}, \quad (30)$$

where we have taken  $1 + \sigma \simeq \sigma = 10\sigma_1$ . Note that  $k_{\pm}$  and  $t_{cr}$  are not free and are determined by other parameters.

### 3.3. Comparison of spectral profiles with $k_{\pm} \ll 1$ case

Regardless of pair effects, the typical frequency of the reverse shock falls in the optical/UV regime, and self-absorption can hardly play a role at the optical (e.g. Sari & Piran 1999b). So the flux behaves as the synchrotron tail  $F_{\nu} \propto \nu^{1/3}$  just below the optical, and  $F_{\nu} \propto \nu^2$  at somewhat lower frequencies where self-absorption is important.

For pari-rich reverse shocks, the typical frequency is far below the optical and the emission there suffer strong self-absorption, so a steep slope 5/2 is apparent in the self-absorption regime of lower frequencies. The spectral indices from low to high frequencies are in the order of  $[5/2, \sim -1/2, \sim -1]$  for  $\nu_a < \nu_c$  (or  $[5/2, \sim -1]$  if  $\nu_a > \nu_c$ ), as shown in Fig. 2. We note that the spectral index 5/2 and stronger fluxes below the optical are the distinct properties of a pair-rich reverse shock. Future spectroscopy observation of prompt emission in longer wavelengths, such as by *REM* (Zerbi et al. 2001), may detect the 5/2 slope in IR spectra, and reveal the pair influence.

## 4. OBSERVATIONS

ROTSE detected a strong optical flash during GRB 990123, which reached a peak of  $\sim 1$  Jy 50 s after the GRB trigger (Akerlof et al. 1999). From Eqs. (21) and (22) a pair-rich reverse shock is easy to emit such a strong flash. Absorption lines in the optical afterglow have inferred a redshift of  $z = 1.6$ , or a luminosity distance of  $d_l = 4 \times 10^{28}$  cm (in a  $H_0 = 71$  km s $^{-1}$ Mpc $^{-1}$ ,  $\Omega_m = 0.27$  and  $\Omega_\Lambda = 0.73$  universe). The released gamma-ray energy is therefore huge,  $E_\gamma \sim 10^{54}$  ergs, so we assume  $E \sim E_a \sim 10^{54}$  ergs. Noting that the peak time is  $t_{cr} \sim 50/(1+z) \sim 20$  s, the other reasonable parameters to achieve a 1-Jy flash are in their typical values:  $\xi_{e,-1} \xi_{B,-2}^{3/4} n_1^{1/2} \gamma_{4,300} \Gamma_{300}^{-1} (1+\sigma)^{-1} \approx 1$ .

However, strong optical flashes appear to be rare, since they have not been detected from other bursts (Akerlof et al. 2000; Kehoe et al. 2001). Especially, GRBs 981121 and 981223 are observed to have flashes, if any, fainter than  $\sim 10$  mJy a few tens seconds after the GRB triggers. To solve this problem in the pair-poor reverse shock model, one needs to assume that the characteristic frequency is either well above or below the optical,  $\nu_m \gg \nu_R$  or  $\nu_m \ll \nu_R$  (Kobayashi 2000). However Soderberg & Ramirez-Ruiz (2002) have investigated a subset of GRBs with afterglow-determined parameters, and shown that strong flashes may be expected in all of these bursts.

For pair-rich reverse shocks, it is usually the case of strong flashes in which the optical emission is independent of the pair numbers (Eqs. (21) and (22)). Since the gamma-ray fluences of GRBs 981121 and 981223 is about one or two orders of magnitude lower than GRB 990123, their released gamma-ray energy is  $E_\gamma \sim 10^{52}$  ergs (Kobayashi 2000) if assuming comparable redshift  $z \sim 2$  ( $d_{l,28} \sim 5$ ). To achieve a faint flux,  $< 10$  mJy, in Eq. (21) one needs some extreme parameter values, e.g.  $\xi_B < 10^{-3}$ . But we expect the fluxes are generally large for typical parameters. The rarity of strong flashes in observation may need some external reasons to account for, for example, dust obscuration of the optical/UV in the star formation regions.

## 5. CONCLUSIONS AND DISCUSSION

In this work we calculate the  $e^\pm$  pair number produced in GRB fireballs, and study their influence on the reverse-shock emission. We have assumed that the intrinsic GRB spectrum, before  $\gamma$ - $\gamma$  absorption, can be extrapolated to very high energy,  $\epsilon_{max} \gg \epsilon_{cut}$ . Our calculation of  $e^\pm$  pair number does not depend on any special model, and is only based on observations. We show that, for typical parameters, the GRB wind/fireball will become pair-rich during the bursting phase, owing to intense  $e^\pm$  pair production. Later on, the pairs are carried into the reverse shock and give rise to the intense prompt flash which peaks at lower frequency, i.e. in the IR band, as opposed to the optical/UV emission in the case where pair-loading is negligible. The emission below the observed peak frequency suffers strong self-absorption, leading to the distinct self-absorption spectral index 5/2.

Since  $k_\pm \propto \Gamma^{-(2\beta-3)} R^{-2}$ , pair loading is unimportant for Lorentz factors large enough (also see Fig. 1). However, the Lorentz factors of GRBs have been found not to be quite large by some previous works. For examples, in the internal shock model of GRBs, the burst emission should come from internal shocks before significant deceleration due to the swept-up external matter, which results in  $\Gamma \lesssim 10^3$  (Lazzaiti, Ghisellini & Celotti 1999); The observed pulse width evolution in the bursting phase seems to rule out the GRB models with  $\Gamma \gg 10^3$  (Ramirez-Ruiz & Fenimore 2000); For GRBs to be efficient, the cooling timescale of leptons should be smaller than the GRB duration, leading to an upper limit of  $\sim 1200$  (Derishev, Kocharovskiy & Kocharovskiy 2001). We, therefore, expect that most GRBs are pair-rich with  $2k_\pm > 1$ .

The pair-rich reverse shocks emit mainly in the IR band. If GRBs are associated with star forming regions, as implied by the observations (e.g., Bloom et al. 1999; Fruchter et al. 1999; Bloom, Kulkarni & Djorgovski 2001) and by the favored progenitor models that GRBs come from explosions of massive stars (Woosley 1993; Paczyński 1998; Vietri & Stella 1999; MacFadyen & Woosley 1999), the optical may suffer dust obscuration, whereas the IR would not (e.g., Draine & Hao 2002; Reichart & Yost 2002; Ramirez-Ruiz et al. 2002; Fruchter et al. 2001; Waxman & Draine 2000). Strong pair-loading also increase significantly the flash brightness. Thus, we expect that there are many strong IR flashes associated with GRBs (and XRFs). If so, the rarity of optical flashes in GRBs will infer dust-enshrouded environment of GRBs. The detection of prompt IR flashes requires rapid response to the GRB trigger in such band, and the up-coming near-IR telescope, *REM* (Zerbi et al. 2001), is capable of catching them.

The observation in high energy range, e.g.,  $\gtrsim 100$  MeV, plays an important role in GRB research, because they provide a way to determine the initial Lorentz factor  $\Gamma$  (e.g. Baring 2000; Lithwick & Sari 2001, and references therein). If a GRB exhibits attenuation above some  $\epsilon_{cut}$ , we can use Eq.(6) together with Eq. (2) to constrain  $\Gamma$ . If  $\epsilon_{cut} \approx 1$  GeV, then we have, for typical parameters,  $\Gamma \gtrsim 230$  where the equality is for  $R \approx R_{var}$  (see the crossing point between curves  $R_{cut}$  and  $R_{var}$  in Fig. 1). The high-resolution spectra of GRBs may be provided by the next generation high-energy gamma-ray observatory, e.g., *GLAST*.

Eq.(8) indicates that  $\sim 10^{54} E_{\gamma,52}^2$  pairs are produced in a GRB. This number should be reduced by a factor of  $\theta_{jet}^2/4$  if GRBs are beamed. It is recently suggested that the annihilation of the relic positrons provides identification beacon for at least one GRB remnant in the Milky way (Furlanetto & Loeb 2002).

We would like to thank the referee for valuable comments. Z. Li thanks D.M. Wei, X.Y. Wang, Y.F. Huang and X.F. Wu for helpful discussions. This work was supported by the National Natural Science Foundation of China (grants 19825109 and 19973003), the National 973 Project (NKBRF G19990754) and the Special Funds for Major State Basic Research Projects.

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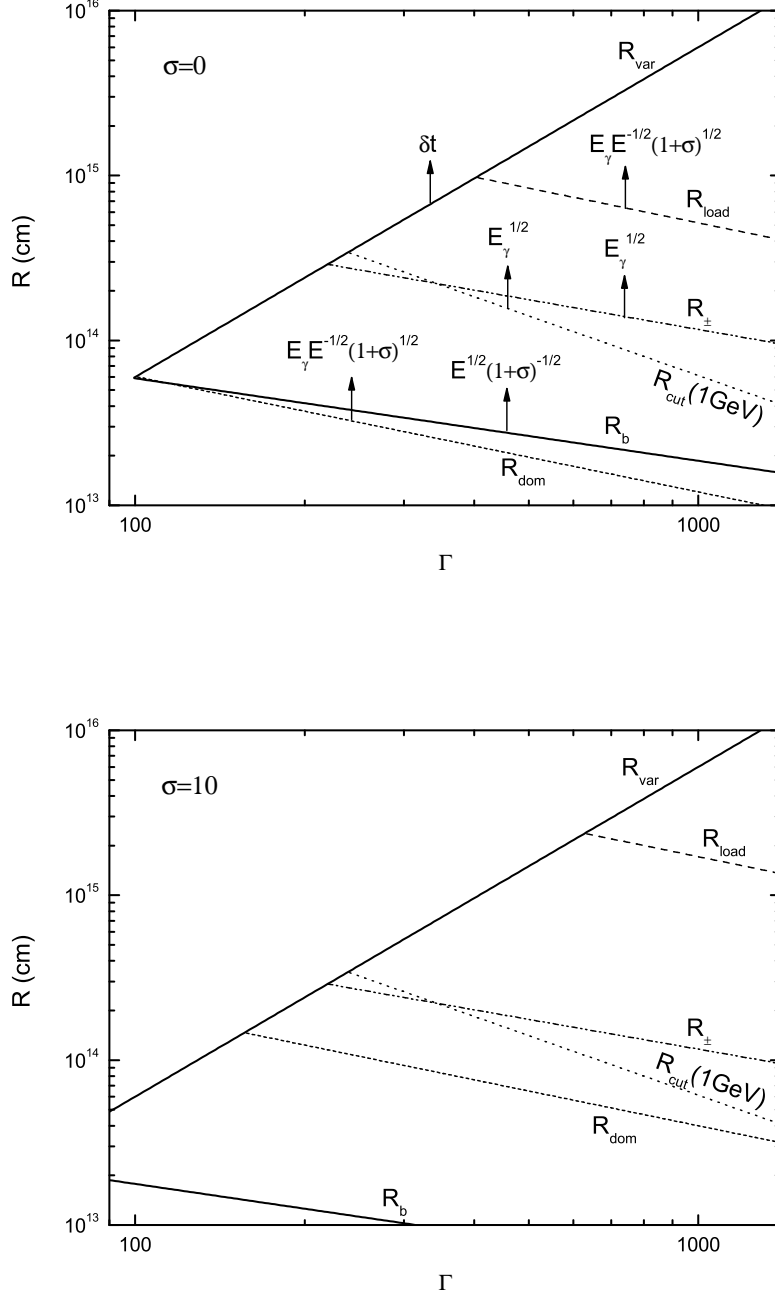


FIG. 1.— Emission site  $R$  versus initial Lorentz factor  $\Gamma$ :  $\sigma = 0$  (upper frame) and  $\sigma = 10$  (lower frame). Neither the regime above  $R_{var}$  nor that below  $R_b$  is relevant to observed GRBs. Below  $R_{load}$  is the regime where pair loading is important,  $2k_{\pm} > 1$ . Case  $2k_{\pm} > m_p/m_e$  is even available below  $R_{dom}$ . A classic GRB, with non-thermal sub-MeV radiation and rapid variabilities, should be optically thin to scattering of photons by baryonic electrons ( $R > R_b$ ) and secondary electron-positron pairs ( $R > R_{\pm}$ ). The X-ray flashes are possible to appear below  $R_{\pm}$ . The GRBs shows no attenuation above 1 GeV correspond to regime beyond the curve marked  $R_{cut}(1\text{ GeV})$ .  $E_{52} = E_{\gamma,52} = \epsilon_b = \delta t_{-1} = 1$  and  $\beta = 2.2$  are assumed. The scaling laws of special radii with the parameters are also marked, except for  $\epsilon_b$  to which the relation is usually weak.

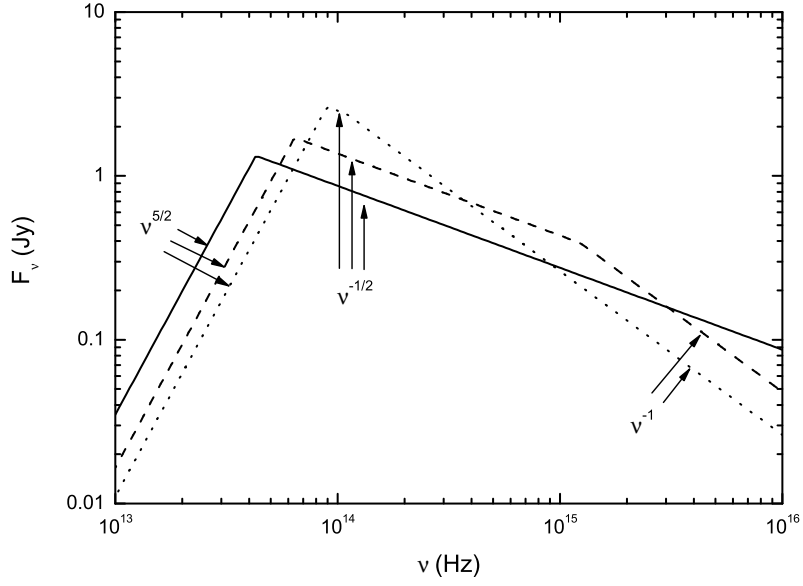


FIG. 2.— Examples of prompt-emission spectra from pair-rich reverse shocks:  $(\xi_B, \sigma) = (0.01, 0)$  (*solid line*),  $(0.2, 5)$  (*dashed line*) and  $(1, 10)$  (*dotted line*), respectively. Other typical parameter values are assumed (see the text), especially that  $k_{\pm, 2} = t_{cr, 1} = 1$ .